APPENDIX D: CALIBRATION OF THE MEASUREMENT SYSTEM

D.1 Introduction

Measurement system calibration is performed prior to and during every RSMS site survey. Calibration curves, as in Figure D-1, showing system noise figure and gain corrections as a function of frequency across the entire frequency range are generated. As measurements are performed, gain corrections are automatically added to every raw data point that is collected. Gain and noise figure curves are used by RSMS operators to determine the relative health of the measurement system, and are also used to pinpoint locations in the measurement system RF path that are operating suboptimally.

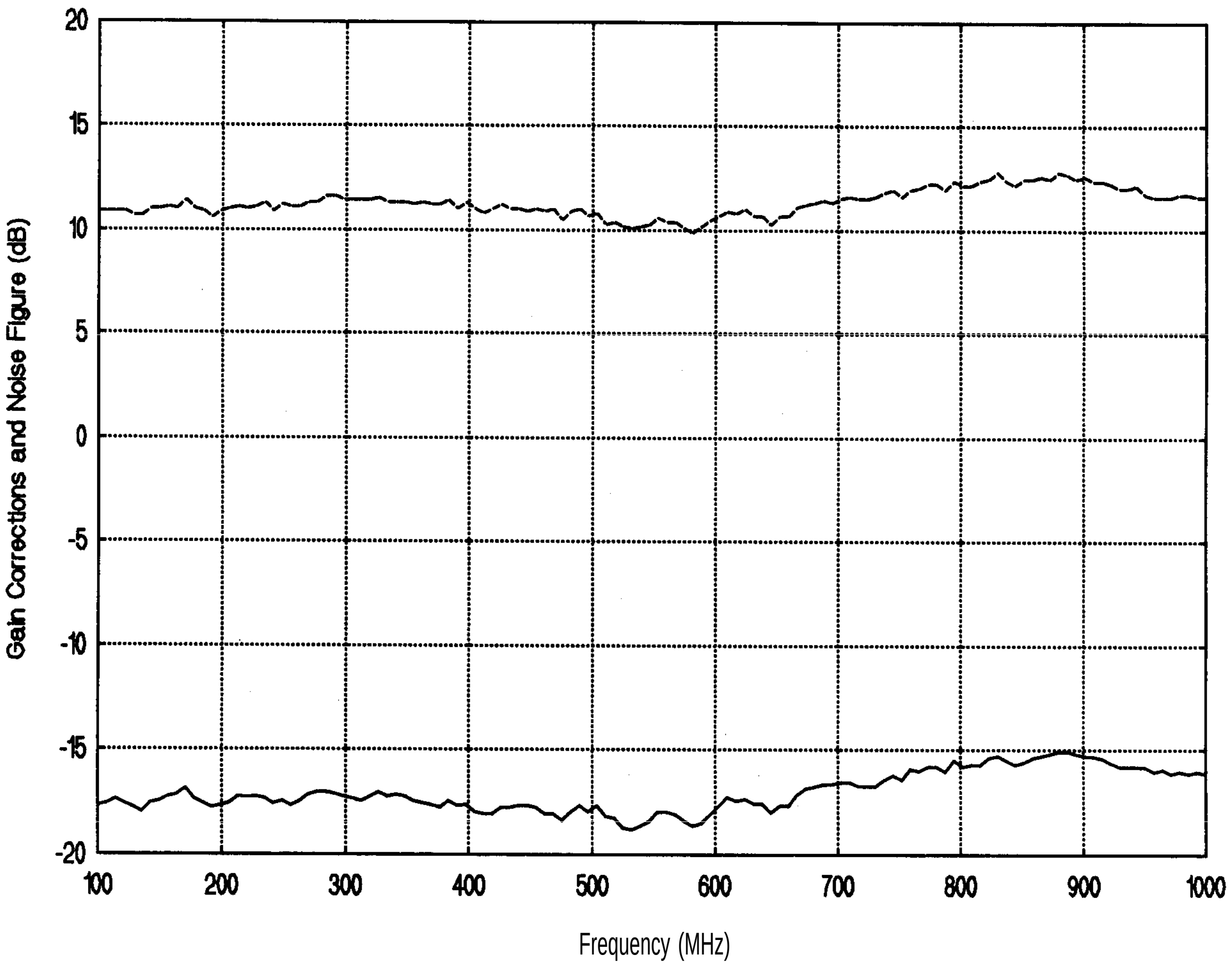

Figure D-1. Example calibration graph for RSMS System-1 showing noise figure (upper; dashed curve) and correction factors (lower; solid curve).

RSMS calibrations are performed exclusively with noise diodes such as the one shown in Figure D-2. Although the technique of noise diode calibration is not as well known in electrical engineering activities as other techniques (e.g., signal generators or vector network analyzers), noise diodes are commonly used for calibration of measurement systems where minimal size, weight, and power consumption are required. Noise diodes provide these features while maintaining high calibration accuracy and this is why they are used for RSMS calibrations.’ This appendix describes the theory and operation of RSMS noise diode calibrations.

Figure D-2. A typical noise diode solid state noise source. A +28-volt potential applied to the BNC connector on the right produces +24-dB excess noise ratio from the type N connector on the left.

‘Another example of noise diode use for measurement system calibration is the Cosmic Background Explorer (COBE) satellite, which recently produced a whole-sky map of 2.5-K background radiation, The same features that make noise diodes attractive for critical satellite calibrations also make them attractive for RSMS work at field locations.

D.2 Theory

RSMS calibrations are implemented as a variant of the y-factor calibration method [1], The y-factor method of amplitude calibration provides for a simple, yet accurate characterization of the amplitude response and noise figure of an RF receiver system. Using noise diodes, amplitude uncertainties of 1 dB in calibration may be achieved in field calibrations over a frequency range of more than 18 GHz.

The noise diode calibration of a receiver tuned to a particular frequency may be represented in simple, lumped-component terms as in Figure D-3. In this diagram, the symbol labelled Σ represents a power-summing function that linearly adds any power at the measurement system input to the inherent noise power of the system. The symbol labelled **g** represents the total gain in the measurement system. The measurement system noise factor is denoted by nf_s, and the input is a noise diode with an excess noise ratio of $\mathbf{enr_d}$.[2]

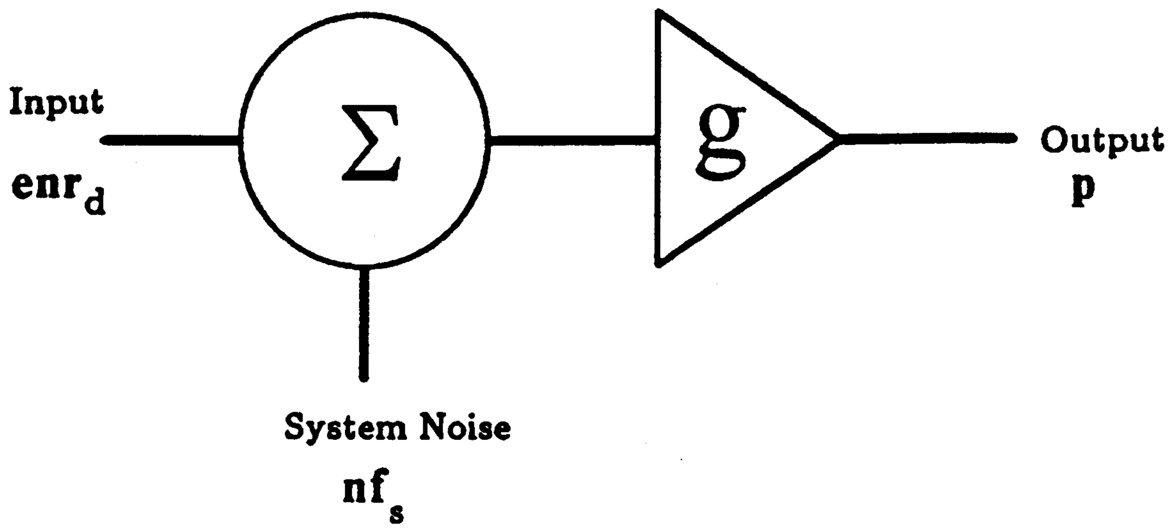

Figure D-3. Lumped-component noise diode calibration schematic diagram; reference equations (Dl) and (D2).

Note that in this appendix all algebraic quantities denoted by lower-case letters, such as "g," represent linear units. All algebraic quantities denoted by upper-case letters, such as "G," represent decibel units. Lower-case and upper-case quantities are connected to each other by the

[2]Many references do not offer a clear explanation of the difference between noise factor and excess noise ratio. Noise factor is the ratio of noise power from a device and thermal noise, (n_{device}/kTB). The excess noise ratio is equal to the noise factor minus one, making it the fraction of power above (in excess of) kTB. The noise figure of a system is defined as 10 log of the noise factor, forcing a solution for noise factor in the calculations. However, since many noise sources are specified in terms of excess noise ratio, that quantity must sometimes be used.

relation (UPPER CASE TERM) = 10log(lower case term); for example, G = 10log(g), or if enr_d = 100 mW, then ENR_d = 20 dBm,

In noise diode calibration, the primary concern is the difference in output signal when the noise diode is switched on and off. For the (noise diode = on) condition, the linear expression is:

$$p_{on} = (nf_s + enr_d) \text{ x } gkTB, \qquad \text{(Dl)}$$

and for the noise diode = off condition:

$$P_{off} = (nf_s) \text{ x } gkTB. \qquad \text{(D2)}$$

The quantity k is Boltzmann’s constant, equal to 1.38 $*10^{-20}$ mW*s/K (milliwatt seconds per kelvin). T is the system temperature in kelvin, and B is the bandwidth in hertz. The ratio of these two quantities is called the Y factor:

$$y = (p_{on}/p_{off}) = (nf_s + enr_d)/(nfs) \qquad \text{(D3a)}$$

$$Y = \text{l0log}(y) = \text{loIog}(p_{on}/p_{off}) = P_{on} - P_{off}. \qquad \text{(D3b)}$$

From equation (D3), we solve for the system noise factor:

$$nf_s = (enr_{d)}/(y-1). \qquad \text{(D4)}$$

The measurement system noise figure is 10 log of the noise factor:

$$NF_s = 10\log(enr_d/(y-1)) \qquad \text{(D5)}$$

$$= ENR_d - 10\log(y-1)$$

$$= ENR_d - 10\log(\text{l0}^{y/10} - 1).$$

Solving equations (Dl) and (D2) for gain, g, yields:

$$g = (p_{on} - p_{off})/(enr_d \text{ x } kTB) \qquad \text{(D6a)}$$

$$G = 10\log(p_{on} - p_{off}) - 10\log(enr_d \text{ x } kTB)$$

$$= 10\log(10^{Pon/10} - 10^{Poff/10}) - ENR_d - 10\log(kTB). \qquad \text{(D6c)}$$

In RSMS calibrations, equation (D6c) is used to calculate gain from measured noise diode values. Note that this calculation utilizes the difference between p_{on} and p_{off}, rather than the y-factor ratio of these values. Thus, the RSMS noise diode calibration is a variant of the standard y-factor calibration technique.

Although equation (D5) could be used to calculate measurement system noise figure, the implementation in RSMS software uses an equivalent equation. It is derived from (D1):

$$nf_s = p_{off}/gkTB \tag{D7a}$$

$$NF_s = 10\log(p_{off}) - 10\log(gkTB) \tag{D7b}$$

$$= P_{off} - G - 10\log(kTB).$$

Substituting expression (D6b) for gain into (D7b) yields:

$$NF_s = P_{off} + ENR_d - (10^{Pon/10} - 10^{Poff/10}). \tag{D7c}$$

In RSMS calibrations, equation (D7c) is used to calculate noise figure. Whenever an RSMS calibration is performed, P_{on}. and P_{off} are measured at 100 frequencies across the frequent y range to be measured, and equations (D6c) and (D7c) are then used to calculate system gain and noise figure for each of those 100 calibration points. The result is the gain response and noise figure of the system as a function of frequency for the frequency range of the measurement. Negative values of the system gain are stored in look-up tables, and are added to raw data values as a correction factor. The gain-corrected power values are stored as spectrum survey data.

Antenna gain corrections are not routinely added to the raw data points as part of RSMS spectrum survey measurements; if incident field strength is required, then antenna correction factors are subtracted separately, after the measurement has been completed. The conversion from power measured in the 50-ohm RSMS circuitry to incident field strength in free space is:

$$FS_{free\ space} = (P_{meas}) + (77.2\ dB) + (20\log(f)) - G_{iso} \tag{D8}$$

where

$FS_{free\ space}$ = incident field strength, dBuV/m;

P_{meas} = power measured in 50 ohms, dBm, corrected for RSMS path gain calibration;

f = measurement frequency, MHz;

G_{iso} = gain of the measurement antenna, dBi (dB relative to isotropic antenna).

Alternatively, if the receiving antenna correction factor (ACF) is known, instead of the antenna gain relative to isotropic, then the incident field strength conversion equation is:

$$FS_{free\ space} = (P_{meas}) + (107\ dB) + ACF \tag{D9}$$

where

ACF = antenna correction factor, dB.

D.3 Application

Excluding the receiving antenna, the entire signal path within the RSMS is calibrated with a noise diode source both before and during a spectrum survey; a noise diode, such as shown in Figure D-2, is connected at thepoint where the RF line attaches to the receiving antenna. The connection may be accomplished manually or via an automatic relay, depending upon the measurement scenario. The noise level in the system is measured at 100 points across the desired frequency range with the noise diode turned on (ON) and turned off (OFF). The RSMS control computer stores all of the ON vs. OFF noise diode values. The control computer then uses the measured difference between ON and OFF at each of the 100 calibration points to solve the calibration equations (D6c) and (D7c) shown above. The gain values are inverted in sign to become correction values. The resulting set of 100 noise figure and gain correction values are stored as a function of system frequency in look-up tables on the computer disk. The frequency-dependent gain-correction curve is used to automatically correct the measured amplitudes of all received signals in subsequent measurements. Figure D-1 shows the gain-correction curve and noise figure curve for a typical RSMS measurement.

This calibration technique has proven very successful for field-deployed radio spectrum measurement systems. It is a fast way to determine sensitivity and gain-correction values for a measurement system, and it is also very useful for isolating the gains and losses through individual components of the measurement system, such as RF lines and amplifiers. Compared to alternative calibration equipment, such as signal generators or vector network analyzers, noise diodes have several advantages:

- The physical size and weight of a noise diode are comparatively small: dimensions are typically less than 5” long and less than an inch diameter; weight is a few ounces.

- Power consumption is low, at about 50 mA of direct current at a +28 volt potential.

- Cost is low, at a few hundred dollars or less for a noise diode.

- Because noise diode sources are inherently broadband (typically 100 MHz to 18 GHz or more), there are no frequency-tracking problems in the calibration, as are encountered with many other calibration techniques.

All of these features lend themselves to measurements in the field, where small size and weight, low power consumption, and simplicity of operation are all at a premium. Moreover the low cost and small requirements for size, weight, and power make it possible to locate several noise diodes at various places in the measurement system, and to carry spares in the event that a noise diode fails. Noise diodes can themselves be calibrated by such entities as the National Institute of Standards and Technology.

At frequencies below 12 GHz, accuracy of noise diode calibration with spectrum analyzers installed in the RSMS is good to within a decibel. At frequencies from 12-18 GHz, accuracy falls to about +,- 2.5 dB due to a higher system noise figure. For noise diodes producing an ENR of about +25 dB, as are used for RSMS measurements, calibrations cannot be performed in a practical sense if system noise figure is more than about 30 dB or is less than about 1 dB. This is because the difference between P_{on} and P_{off} becomes too small to measure reliably in the first case, and too close to the rated ENR of the noise diode to measure reliably in the second case. Noise diode calibrations will not provide information on phase shift as a function of frequency; if a measurement system must be calibrated for phase shift, then additional or alternative calibration methods must be used.

D.4 Reference

[1] S. Adam, *Microwave Theory and Applications,* Englewood Cliffs, NJ: Prentice-Hall, Inc., 1969, pp. 490-502.

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NTIA is responsible for managing the Federal Government's use of the radio spectrum. In discharging this responsibility, NTIA uses the Radio Spectrum Measurement System to collect data for spectrum utilization assessments. This report details such a data collection effort spanning all of the spectrum from 108 MHz to 19.7 GHz in the metropolitan area of San Diego, California, during February and March of 1995.

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